THEORETICAL AND EXPERIMENTAL INVESTIGATIONS
OF COLLECTIVE MICROWAVE PHENOMENA IN SOLIDS

under the direction of
M. Chodorow

Semi-Annual Status Report No. 3
for
NASA Research Grant NGR-05-020-165
National Aeronautics and Space Administration
Washington, D. C. 20546

N68-11878

GPO PRICE $ ________

CFSTI PRICE(S) $ ________

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

for the period
1 April to 30 September 1967

M. L. Report No. 1599
November 1967

Microwave Laboratory
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California

N68-11878
(ACCESSION NUMBER) (THRU)
19
(PAGES) (CODE)
CR-90751 26
(NASA CR OR TMX OR AD NUMBER) (CATEGORY)
FF No. 602(C)

PRECEDING PAGE BLANK NOT FILMED.

ABSTRACT

I. MICROWAVE AMPLIFICATION IN HIGH RESISTIVITY GaAs

Several two-port amplifier configurations have been tested experimentally, starting from GaAs of nominal resistivity 600 ohm-cm. The rf experiments were conducted in a frequency range from 500 to 2000 MHz. Results were in general agreement with the theory. Results to date indicate that the electronic gain is of the order of 30 dB and is broadband.

II. GUNN OSCILLATOR NOISE STUDIES

A theory has been developed on noise and uses a hypothesis of field dependent trapping which requires practical corroboration. Means are now being examined for the development of materials with parameters which may be accurately measured and controlled. The apparatus to make the material is being procured, and measurement techniques for deep level traps are being sampled out. Oscillators have been made from donated materials and these have been successfully operated in the LSA mode. A computer simulation has been made available of the Gunn oscillation and this has been adapted to the circuit controlled case (LSA).

III. ELECTROACOUSTIC AMPLIFIERS

The possibility of using electrostrictive materials for acousto-electric amplification is considered. The properties of one such material, reduced SrT_iO_3, are suitable for amplification above 1 GHz at low temperatures. Preliminary attempts to produce material of the required resistivity are reported.

INTRODUCTION

The work under this Grant is generally concerned with communication and information processing in space satellites and more particularly concerned with exploring new devices, particularly solid-state and optical devices, suitable for generation and modulation of electromagnetic waves in the microwave range and upward through the millimeter and optical frequency ranges. Three projects were active under this Grant during the reporting period:

I. Microwave Amplification in High Resistivity GaAs

II. Gunn Oscillator Noise Studies

III. Electroacoustic Amplifiers

During this period two papers, prepared under the sponsorship of this Grant, were written and submitted for publication:

P.N. Robson, G.S. Kino and B. Fay, "Two Port Microwave Amplification in Long Samples of GaAs," Microwave Laboratory Report No. 1553 (July 1967); submitted to IEEE Trans. ED.

I. Kuru, P.N. Robson and G.S. Kino, "Some Measurements of the Steady State and Transient Characteristics of High Field Dipole Domains in GaAs," Microwave Laboratory Report No. 1567 (August 1967); submitted to IEEE Trans. ED.

Another paper, related to the work underway on this Grant, has been written under the sponsorship of other auspices and submitted for publication:

J.A. Higgins, V.J. Grande and G.L. Pearson, "Signature of the LSA Mode," to be published in the October issue of IEEE Trans ED.

In addition, a comprehensive report on the "Continuous Deflection of Laser Beams" project has been written. This project, reported in the preceding Semi-Annual Status Report (M. L. Report No. 1546), has been completed and this report summarizes the whole project:

E.G.H. Lean, "Studies of Microwave Shear Waves in Solids," Internal Memorandum, Microwave Laboratory Report No. 1543, Stanford University (May 1967).

The Responsible Investigator for this Grant is M. Chodorow.

PRESENT STATUS

I. MICROWAVE AMPLIFICATION IN HIGH RESISTIVITY GaAs

(G. S. Kino, J. Ruch, B. Fay)

INTRODUCTION

The objective of this investigation is to determine the conditions of feasibility of a unilateral two-port microwave amplifier, exploiting the negative conductance property of GaAs biased beyond a threshold field of approximately 3000 volts per cm.

The preliminary work has consisted mainly of verifying the static behavior of high resistivity GaAs diodes above threshold by means of current-voltage characteristic curves and direct potential probing with a traveling capacitive probe, as discussed in the previous report.

PRESENT STATUS

We are now concerned with the problem of realizing a working two-port distributed amplifier. In a two-port amplifier configuration, the rf signal is applied near the cathode contact, exciting a slow space change wave which travels toward the anode with a velocity equal to the electron drift velocity and is amplified in the process because of the negative conductance of the medium.

A small-signal one-dimensional analysis of the signal growth predicts that when the total rf current through the diode is zero, the rf electric field, E_1, is given by

$$E_1(z) = C \exp\left\{ j\omega[t - \int dz/v] - \int \omega_c \, dz/v \right\} , \tag{1}$$

where C is a constant dependent on the excitation, z the distance along the sample, v is the electron drift velocity at the plane z, ω_c is the dielectric relaxation frequency defined by the relation $\omega_c = qn(dv/dE)/t$, q is the electronic charge, n is the number density of electrons at the plane z, and E is the applied electric field.

Because the static electric field is nonuniform with distance, it is essential to express analytically the functional dependence of drift velocity upon electric field. A convenient approximation which can be made to fit the experimental GaAs velocity-field curve of Ruch and Kino over most of the range of interest is

$$\frac{1}{v} = A + BE \qquad (2)$$

with

$$A = 2.5 \times 10^{-8} \text{ sec/cm}$$
$$B = 0.64 \times 10^{-11} \text{ sec/volt} \quad .$$

This approximation results in simple expressions for the growth factor

$$G = \exp \left\{ - \int_0^{\ell} \omega_c \, dz/v \right\}$$

and the phase delay

$$\theta = \omega \int_0^{\ell} dz/v \quad ,$$

where ℓ corresponds closely to the length of the diode. Thus we have

$$G = \exp \left[- \int_0^{\ell} \frac{qn}{\epsilon v} \left(\frac{dv}{dE} \right) \right] dz = \exp \int_0^{\ell} \frac{J}{\epsilon} \frac{d}{dE} \left(\frac{1}{v} \right) dz = \exp J B \ell / \epsilon \qquad (3) .$$

where J is the displacement current density and

$$\theta = \omega \int_0^{\ell} \frac{dz}{v} = \omega \int_0^{\ell} dz(A + BE) = \omega(A\ell + BV) \qquad (4)$$

where V is approximately the applied voltage.

In a first series of experiments, the signal was injected and extracted by means of two capacitively coupled probes, placed in close proximity to one face of a diode as shown schematically in the insert of Fig. 2. Typical sample dimensions in this case were 35 mils in length and 60×60 $(\text{mils})^2$ in cross section. The spacing between the 2 probes was 28 mils, with the injecting probe positioned 4 mils from the cathode contact.

Due to the inherently weak coupling no net gain was observed, but rather a reduction in loss from -100 dB when the bias field was below threshold (direct interprobe pick-up), to -60 dB at the maximum gain point above threshold. The measured phase delay vs voltage and relative voltage vs current gain for one such sample are given in Figs. 2 and 3, respectively. In both curves we note a linear relationship, as predicted by (3) and (4), up to a maximum voltage or current, above which the drift velocity saturates and the approximation given by (1) is no longer valid.

A second series of experiments was conducted adopting the configuration depicted in Fig. 4. The rf signal is now injected and extracted via two narrow strips of gold germanium evaporated onto one face of the sample and alloyed to make ohmic contact. These strips were typically 3 mils wide and spaced 3 - 4 mils from the nearest end contacts.

The parasitic coupling between input and output with the device turned off now decreased to -30 dB because no special care was taken to shield the input and output terminals from each other.
Typical results taken at 960 MHz for a device with $nL = 2.9 \times 10^{11}$ cm^{-2} (L, the length of the sample, is 860μ and a spacing from center to center of the input and output contacts of $\ell = 640\mu$), are shown in Fig. 5. A net unsaturated gain of 2 dB is indicated with a saturated output power of -10 dBm. In the same figure a plot of the variation of output power with respect to bias voltage, with an input power of -20 dBm, is given. Similar results have been obtained at spot frequencies in the range from 800 MHz to 1.5 GHz. In all cases, the input and output contacts were connected through small capacitors (Fig. 1) to 50 ohm coaxial input and output leads, and no tuning of any kind was used.

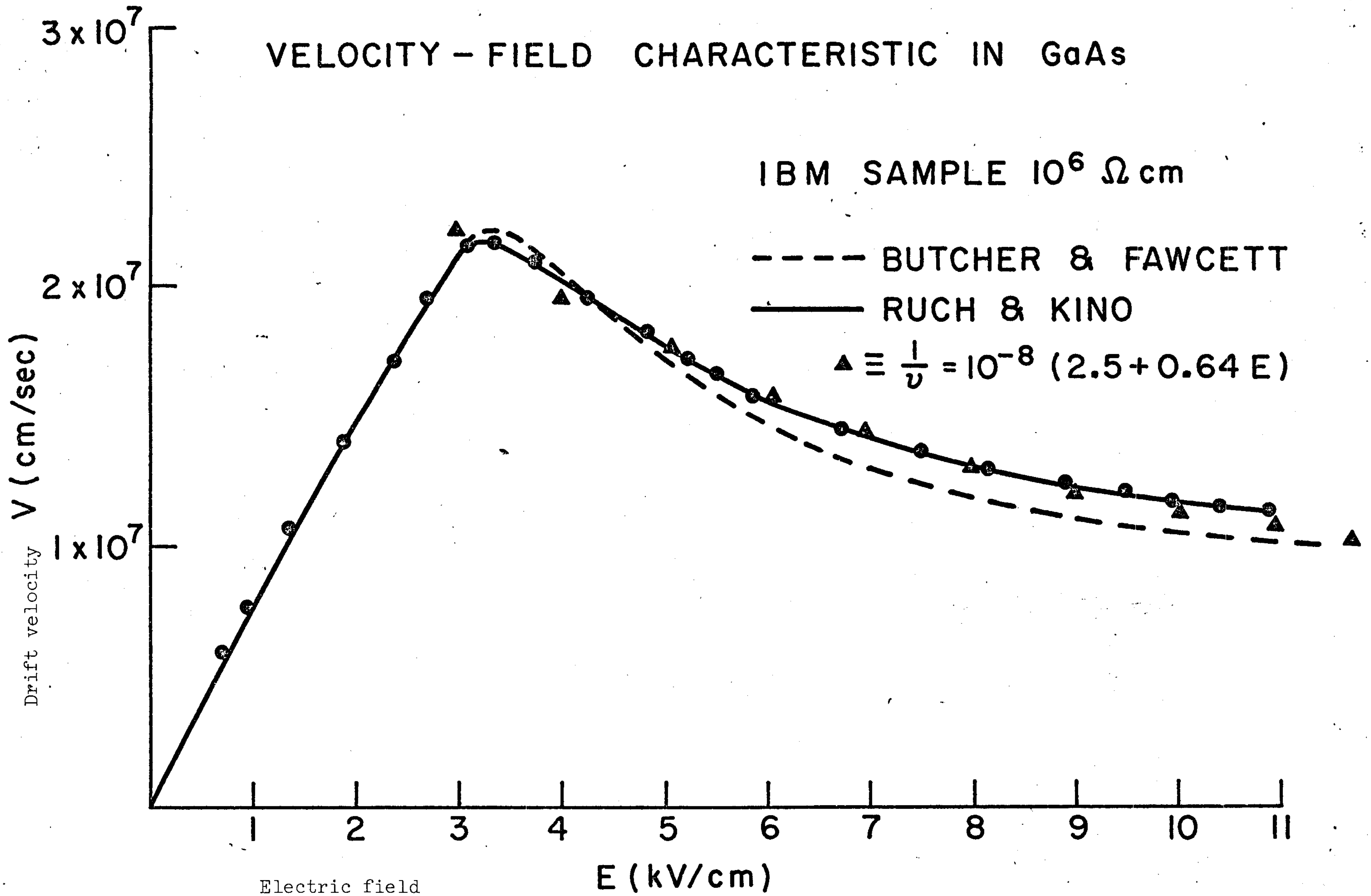

FIG. 1--Fit of curve $1/v = A + BE$ to the Ruch-Kino measured velocity field characteristic.

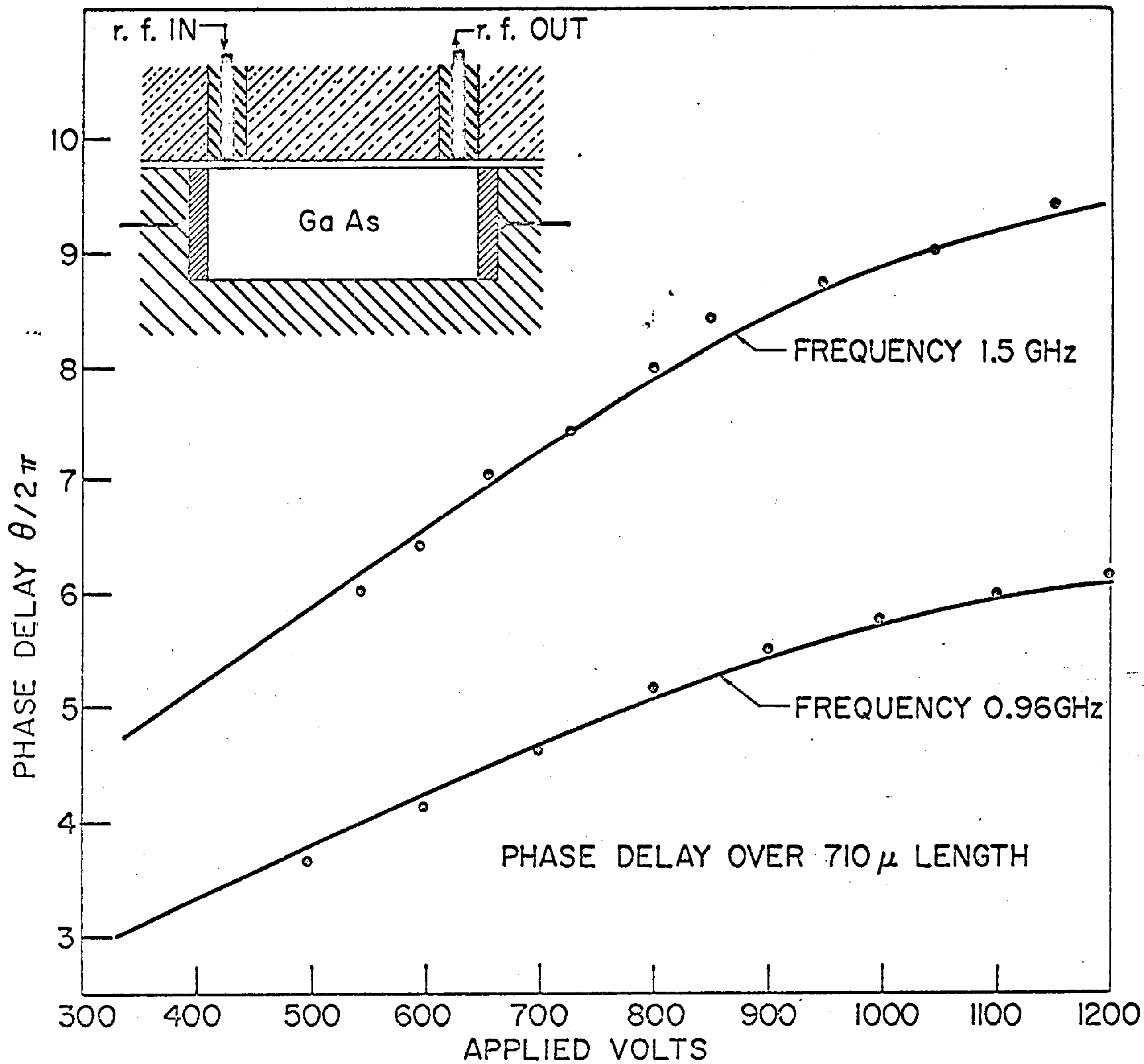

FIG. 2--Measured and theoretical phase delays at 0.96 GHz and 1.56 GHz vs bias voltage.

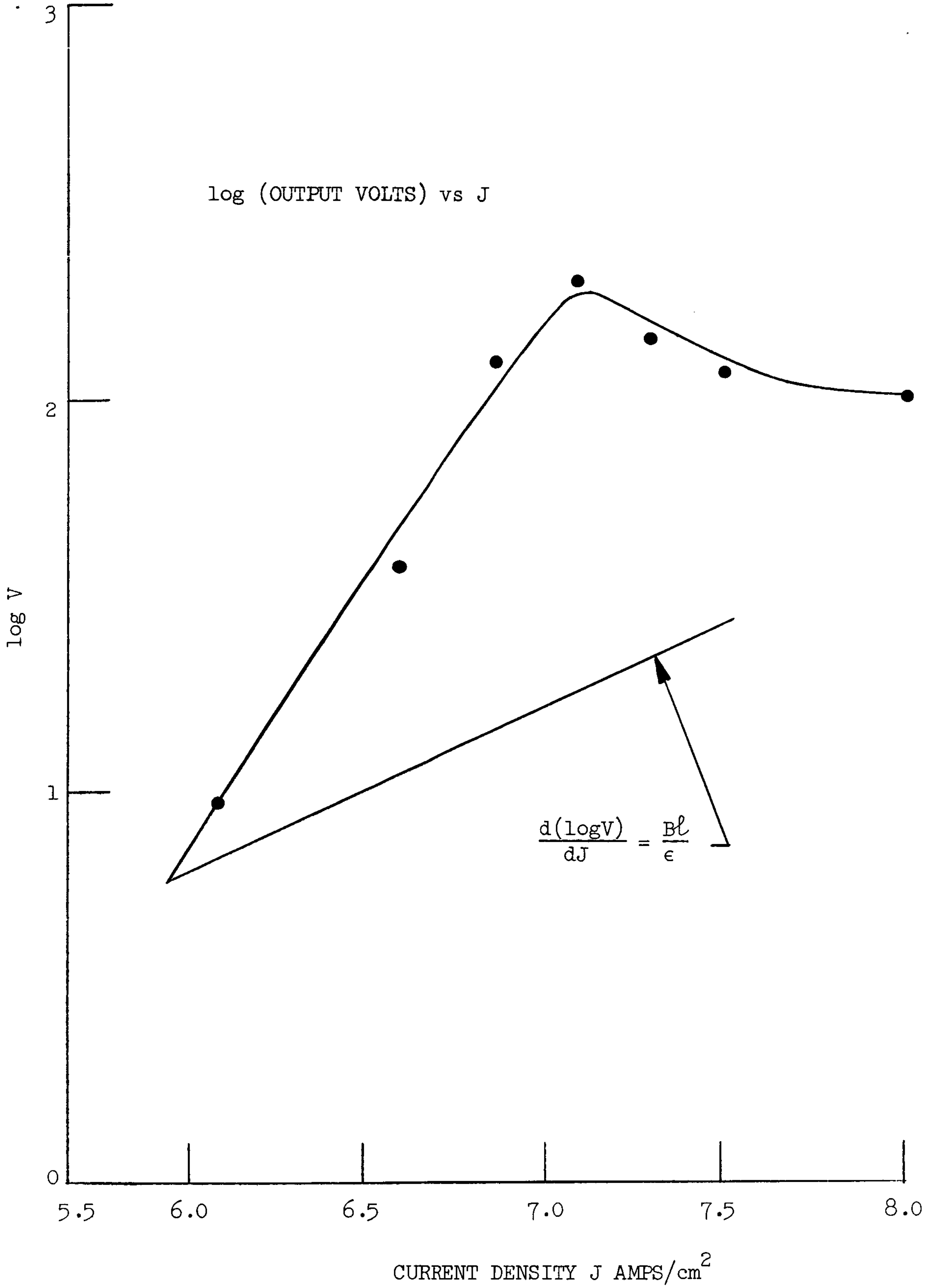

FIG. 3--Log (output volts) vs bias current density at 0.96 GHz.

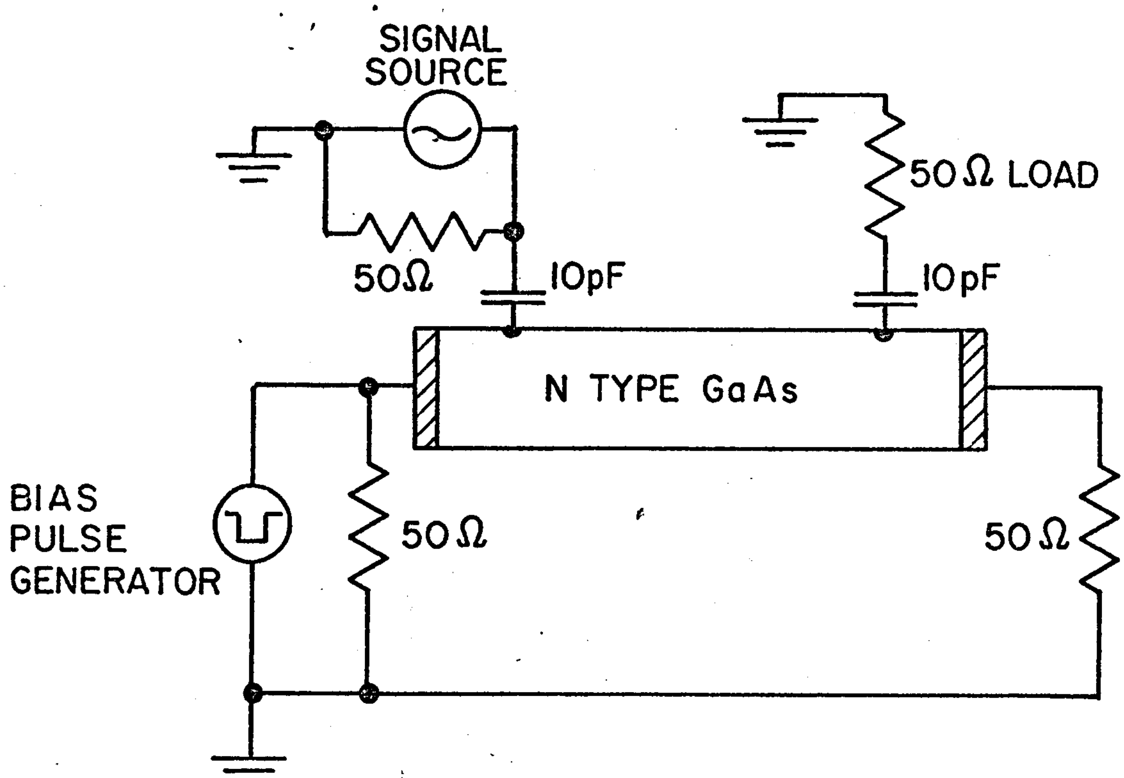

FIG. 4--Schematic layout of circuit for amplifier experiments.

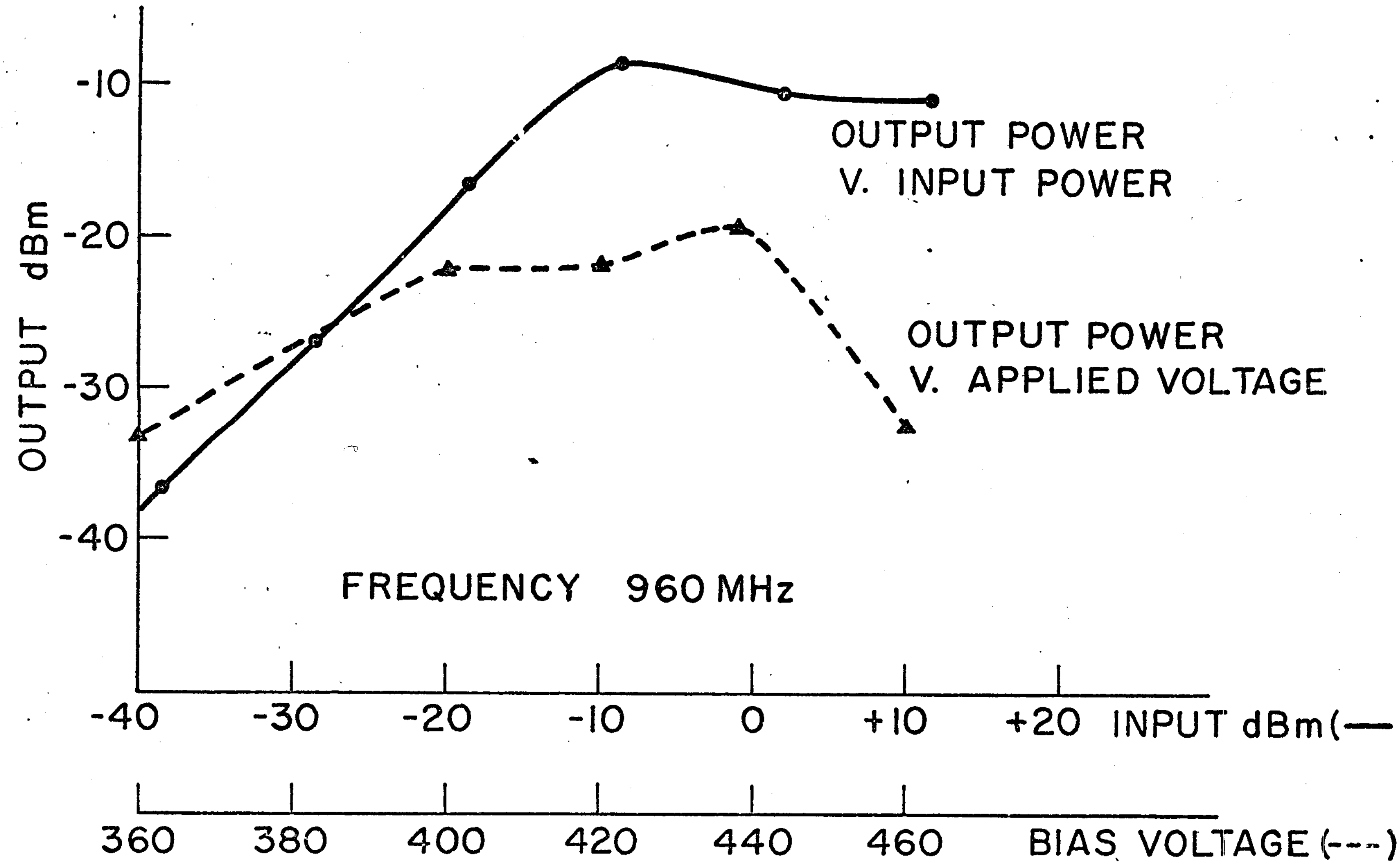

FIG. 5--Output power vs input power at 960 MHz (solid curve), and output power vs applied voltage for an input power of -20 dBm (dahsed curve).

Again with this configuration no signal above that of direct coupling was observed when the input and output couplers were reversed.

More detailed calculations which will be reported elsewhere indicate that in this device the input and output impedances of the system were of the order of 1000 ohms. Thus we would, in this situation, expect considerable coupling loss both at the input and the output. At the present time we are working on methods to improve the coupling.

The results obtained so far indicate that the electronic gain is of the order of 30 dB and is broadband, as would be expected from the theory. All the experimental results obtained are in fair agreement with theoretical results based on the use of the Butcher-Fawcett velocity-field curve. We would expect that in the future with improvement of the coupling we should be able to obtain broadband net gains of the order of 25 dB or more and to increase the saturated power output by at least an order of magnitude with devices of the present size. There should also be no difficulty in operating these devices CW provided that suitable material with a positive or very small resistance-temperature coefficient can be obtained.

II. GUNN OSCILLATOR NOISE STUDIES

(C. F. Quate, J. A. Higgins)

INTRODUCTION

This investigation is concerned with noise in GaAs oscillators. The emphasis initially is on FM noise in two types of bulk GaAs oscillators with the object of correlating noise with the properties of the material. Work to date has been mostly theoretical, although work on some preparatory practical aspects of constructing experimental oscillators has been undertaken.

PRESENT STATUS

Noise Theory

A theory has been developed which could be an explanation of the major contributor to FM noise in Gunn oscillators. The theory rests on the hypothesis that the high fields in the Gunn domains give rise to fluctuations or changes in the free carrier concentration. Carrier concentration will affect dipole velocity and if, as hypothesised, the carrier concentration fluctuations have long relaxation times to equilibrium, then the velocity of the dipoles will have an autocorrelation function which gives rise to a "1/f" power distribution of noise in the base band (0 to 10 Mc/s), which is the observed phenomenon. The extent or magnitude of the carrier concentration fluctuations may be shown to be proportional to the number of deep donor levels in the material. A practical demonstration of this theory would be to correlate the number of impurity levels, such as traps, to the level of the noise spectrum and to link dipole velocity fluctuations to carrier concentration fluctuations. The theory shows how the noise level may be affected by a cavity controlling the device and, in the extreme case, why one should expect a much lower FM noise level from the LSA mode of oscillation.

Device Fabrication

Many devices have been made from GaAs in both bulk samples and layers. The bulk material gave good performance as both Gunn oscillators and LSA mode oscillators. The LSA oscillations have been observed at 4 and 7 GHz. The circuit used to observe the LSA mode at 4 GHz gave a good representation of the change-over from Gunn to LSA modes. This was reported at the Solid State Devices Conference at Santa Barbara in the early summer. It is a confirmation of Copeland's computed predictions.[1] Figure 1 shows this transition.

On epitaxial material, no repeatable success has been achieved with the problem of making adequate electrical contacts. Gold-germanium eutectic alloy seems to be unreliable for forming contacts, and a new silver-germanium base alloy promises more success in this respect. Oscillations at approximately 4 GHz have, however, been observed in materials from Varian and Texas Instruments. Schottky barrier and Van de Pauw measurements were carried out on each material.

Apparatus and materials have been obtained to initiate our own liquid epitaxy growing facility.

Computer Simulations of GaAs Oscillators

Harker's[2] computer program, which is capable of completely calculating and plotting the growth and propagation of domains in GaAs bulk devices, has been successfully transfered to the IBM 360 facility and language. This program is now being worked on extensively: (a) to convert it to a circuit controlled case study, (LSA), where it will be used to examine in detail the effects of carrier level fluctuation on frequency and noise; and (b) to convert it to allow the use of more exact laws for the electron distribution between the two valleys of GaAs and other compound semiconductors.

---

[1] J.A. Copeland, "LSA Oscillator Diode Theory," Appl. Phys. 38 (July 1967).

[2] K.J. Harker, "Gunn Effect Theory," in Quarterly Status Report for Contract AF 30 (602)-3595, Microwave Laboratory Report No. 1588, Stanford University (October 1967).

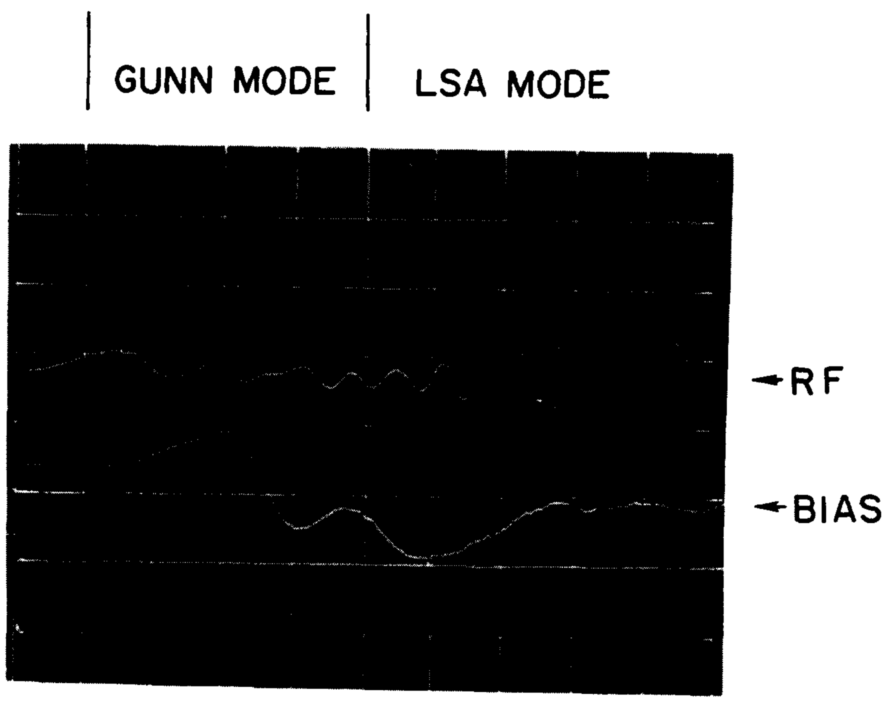

FIG. 1--Transition for a transit time frequency of oscillation to an LSA mode of oscillation. Time scale is 0.5 nsec/cm; volts scale is 20 v/cm.

III. ELECTROACOUSTIC AMPLIFIERS

(C.F. Quate, D. Jefferies)

INTRODUCTION

In addition to the work on piezoelectric semiconductors as reported in the preceding status report, we are considering the possibility of using ferroelectric semiconductors about their Curie point. In these semiconductors the electrostriction component is used to obtain coupling to the electrons in a manner first described by Pekar.[1] The system has the advantage of exhibiting a much stronger coupling for longitudinal waves than for shear waves. Couplers for longitudinal waves are more efficient than shear wave couplers at the present stage, and we therefore see some advantage in longitudinal wave amplifiers.

PRESENT STATUS

Electrostrictive media are characterized by quadratic dependence of the stress T on the electric field E, namely,

$$T = cS + gE^2$$

where

S = Strain

c = Elastic constant

g = Electrostrictive constant

while piezoelectric media exhibit the linear dependence given by

$$T = cS - eE$$

where e is a piezoelectric constant. An electrostrictive material

[1] S.I. Pekar, Soviet Physics. JETP 22 (Feb 1966).

biased by a uniform static electric field E_0 becomes formally equivalent to a piezoelectric medium with piezo-coefficent

$$e = -2gE_0 \quad .$$

The theory of acoustic amplification in piezoelectric semiconductors developed by White[2] may be applied directly to the electrostrictive case, with the modification that the coupling constant K is proportional to the field

$$K^2 = 4 \frac{g^2 E_0^2}{\epsilon c}$$

where ϵ = permittivity.

Reduced strontium titanate, $SrTiO_3$, is a suitable electrostrictive medium for the study of acoustic amplification in the microwave region when used at a temperature slightly above the cubic-tetragonal phase transition at 110°K.[3] Values for the dielectric[4] and electrostrictive[5] constants reported in the literature indicate that the square of the coupling constant is $K^2 = 3.8E_0^2 \times 10^{-10}$ at 110°K (E_0 in V/cm). In piezoelectric semiconductors used for acoustic amplification, K^2 is of the order 0.05. This value of K^2 is reached with applied fields of the order 10^4 V/cm in $SrTiO_3$. The electron mobility in $SrTiO_3$ at 110°K is of the order of 100 cm^2/Vsec[6] and the longitudinal sound velocity is 7.8 $\times 10^5$ cm/sec[7] so the bias field also serves to drift the carriers slightly faster than the sound velocity. A typical gain-field curve calculated from the modified theory is shown in Fig. 1. It should be possible to obtain 90 dB of acoustic gain at 14 gHz using a sample of length 0.02 cms to amplify longitudinal waves. The room temperature resistivity of the active medium would be 10 Ω cms.

---

[2] D.L. White, J. Appl. Phys. 33, 2547 (1962).

[3] L. Riami and G.A. de Mars, Phys. Rev. 127, 702 (1962).

[4] H.E. Weaver, Phys. Chem. Solids 11, 274 (1959).

[5] W.H. Winter and G. Rupprecht, Bull Am. Phys. Soc. 7, 438 (1962).

[6] H.P.R. Frederiske, W.R. Thurber, and W.R. Hosler, Phys. Rev. 134, A442 (1964).

[7] R.O. Bell and G. Rupprecht, Phys. Rev. 129, 90 (1963).

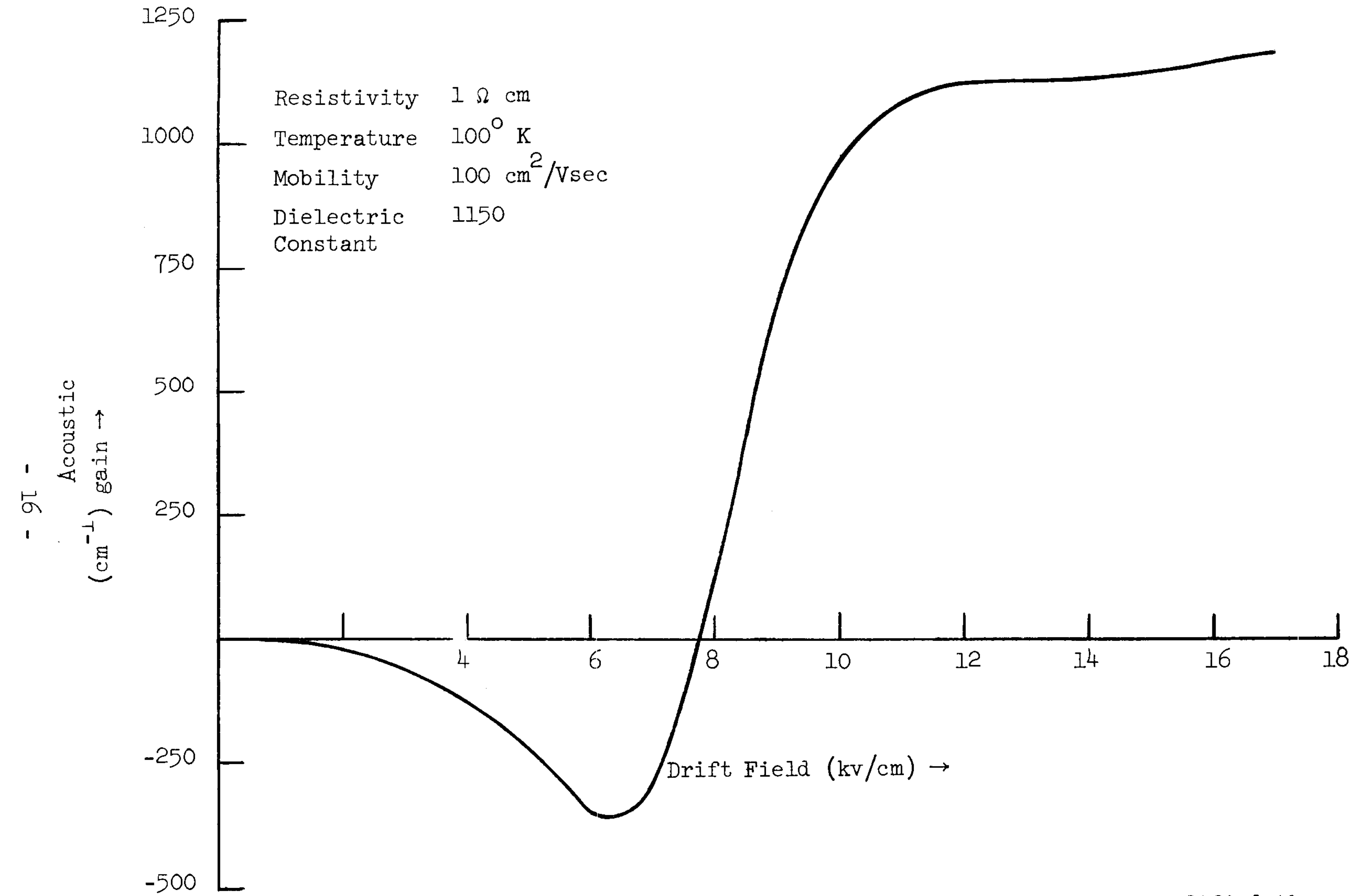

Fig. 1 Acoustic gain in $SrTiO_3$ calculated from the modified theory.

We have prepared some highly conductive [$\rho \simeq 5 \times 10^{-3}$ Ω cms] reduced $SrTiO_3$ by heating an insulating crystal in hydrogen at $1200^\circ C$. Ohmic contacts have been made to this material using evaporated films of titanium covered with gold. It should be possible to observe current oscillations of the type reported by Haydl[8] for fields slightly above synchronism; however because of the low resistivity we have not been able to achieve synchronous fields. Effort is continuing to produce higher resistivity material.

[8] W.H. Haydl, "Current Instabilities in Piezoelectric Semiconductors," Microwave Laboratory Report No. 1517, Stanford University (March 1967).